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Final Technical Report for:

FAR INFRARED ALL-SKY SURVEY

(Grant NAGW-2121)

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BACKGROUND

Precise measurements of the angular power spectrum of the Cosmic Microwave Background (CMB) anisotropy will revolutionize cosmology. These measurements will discriminate between competing cosmological models and, if the standard inflationary scenario is correct, will determine each of the fundamental cosmological parameters with high precision. The astrophysics community has recognized this potential: the orbital experiments MAP and PLANCK, have been approved to measure CMB anisotropy. Balloon-borne experiments can realize much of this potential before these missions are launched. Additionally, properly designed balloon-borne experiments can complement MAP in frequency and angular resolution and can give the first realistic test of the instrumentation proposed for the high frequency instrument on PLANCK.

The MAXIMA experiment is part of the MAXIMA/BOOMERANG collaboration which is doing balloon observations of the angular power spectrum of the Cosmic Microwave Background from $\ell = 10$ to $\ell = 800$. These experiments are designed to use the benefits of both North American and Antarctic long-duration ballooning to full advantage. We have developed several new technologies that together allow the power spectrum to be measured with unprecedented combination of angular resolution, beam throw, sensitivity, sky coverage and control of systematic effects. These technologies are the basis for the high frequency instrument for the PLANCK mission. Our measurements will strongly discriminate between models of the origin and evolution of structure in the universe and, for many models, will determine the value of the basic cosmological parameters to high precision.

The MAXIMA gondola being prepared primarily at Berkeley is optimized for conventional northern hemisphere ballooning. It uses 100 mK spider bolometers in a focal plane with 16 high efficiency single-color 11 arcmin pixels. The primary mirror will scan 4 degrees peak-to-peak at 0.5 Hz while the gondola makes a raster scan of >2000 pixels with sensitivity extending to $\ell \sim 800$. The first science flight (MAXIMA-1) will take place from Palestine, TX, in summer 1998 when a very low dust region of the sky is accessible.

PROGRESS DURING 7/1/90-1/31/97

Much valuable information was obtained by analyzing the results of an engineering flight (MAXIMA-0) in FY95. New systems tested on that flight include the telescope, gondola, attitude control system, telemetry, spider bolometers, primary mirror modulation, scan strategy, etc. Most of these systems performed remarkably well. One significant difficulty was encountered with the new attitude control system. Pendulum motion of the gondola large enough to complicate scientific data analysis was observed. Subsequent ground tests with second generation attitude control software showed that the damping of this motion was inadequate for good performance on either MAXIMA or BOOMERANG. Passive pendulation dampers were designed for use on both gondolas.

Most of the MAXIMA activity for the grant period has been preparation for the first science flight which can be summarized as follows:

- The new MAXIMA gondola was refurbished and prepared for flight.
- Testing and analysis was done on the attitude control system to improve its performance.
- A new three-axis magnetometer was fabricated and installed.
- Cryostat tests were completed.

- ^3He and ADR refrigerators were installed.
- Fabrication of detector assemblies was completed (including feedhorns, filters and bolometer supports).
- Bolometers were furnished by the Caltech group for preliminary tests.
- Low temperature JFET amplifiers were fabricated and installed.
- Cryostat wiring was installed.
- Ambient temperature AC bias electronics was fabricated in collaboration with the Caltech group and tested.
- Cooled secondary and tertiary mirrors were tested and installed.
- Ambient temperature detector amplifiers were interfaced to the telemetry system.
- Cryostat supports were fabricated and the cryostat was installed in the gondola.

PLANS FOR 1997-98

The MAXIMA/BOOMERANG collaboration has been approved for another cycle of NASA funding (NAG5-4454). During the next year, intensive effort will be devoted to final flight preparations and flights of MAXIMA and BOOMERANG to obtain large high quality data sets.

Work on MAXIMA will focus on bolometer testing and production of a second generation of detectors, reducing the infrared background on the bolometers and on improving the optical coupling of the bolometers. The entire telescope system will be extensively tested and improvements made to insure reliability. Early in 1998 the focus will shift to preparations for the MAXIMA-1 science flight. A sky region with very low dust emission and facilities for the required evening launch will be available in June from Palestine, Texas. Observations are planned for a region between 15 and 30 degrees from the North celestial pole. Scans at two

elevation angles will be used to obtain cross linked maps of more than 10,000 pixels. If the system performs satisfactorily and the gondola is not damaged, a second flight is planned for August 1998.

This experimental program will produce an unprecedented amount of data. We anticipate a data set of ~10,000 independent pixels, larger than that for the COBE/DMR. Plans are being made and collaborations arranged to carry out the massive data analysis task. This grant will primarily support hardware development and balloon operations.

PUBLICATIONS

M.L. Fischer, D.C. Alsop, A.C. Clapp, D.A. Cottingham, A.E. Lange, P.L. Richards, G. Smoot, J.O. Gundersen, T.C. Koch, P.R. Meinhold, P.M. Lubin, E.S. Cheng, and E. Kreysa, A Millimeter-Wave Anisotropy Experiment (MAX) to Search for Anisotropy in the Cosmic Background Radiation on Medium Angular Scales, in AIP CONFERENCE PROCEEDINGS 222, After the First Three Minutes, College Park, MD 1990, Editors: Stephen S. Holt, Charles L. Bennett, and Virginia Trimble (American Institute of Physics, New York, 1991) pp. 123-128.

D.C. Alsop, A.C. Clapp, D.A. Cottingham, M.L. Fischer, A.E. Lange, P.L. Richards, G. Smoot, J.O. Gundersen, T.C. Koch, P.R. Meinhold, P.M. Lubin, E.S. Cheng, and E. Kreysa, MAX, A Millimeter-Wave Anisotropy Experiment to Search for Anisotropy in the Cosmic Background Radiation on Intermediate Angular Scales, in Trends in Astroparticle Physics, (World Scientific Publishers, Singapore, 1992) p. 252.

M.L. Fischer, D.C. Alsop, E.S. Cheng, A.C. Clapp, D.A. Cottingham, J.O. Gundersen, T.C. Koch, E. Kreysa, P.R. Meinhold, A.E. Lange, P.M. Lubin, P.L. Richards, and G.F. Smoot, A Bolometric Millimeter-Wave System for Observations of Anisotropy in the Cosmic Microwave Background Radiation on Medium Angular Scales, *Astrophys. J.* 388, 242 (1992).

D.C. Alsop, E.S. Cheng, A.C. Clapp, D.A. Cottingham, M.L. Fischer, J.O. Gundersen, E. Kreysa, A.E. Lange, P.M. Lubin, P.R. Meinhold, P.L. Richards, and G.F. Smoot, A Search for Anisotropy in the Cosmic Microwave Background on Intermediate Angular Scales, *Astrophys. J.* 395, 317 (1992).

M.L. Fischer, P.L. Richards, D.C. Alsop, A.C. Clapp, D.A. Cottingham, A.E. Lange, G. Smoot, J.O. Gundersen, T.C. Koch, P.R. Meinhold, P.M. Lubin, E.S. Cheng, and E. Kreysa, A Status Report on MAX, A Millimeter-Wave Anisotropy Experiment to Search for Anisotropy in the Cosmic Background Radiation on Intermediate Angular Scales, in the Int. School of Astrophysics "D. Chalonge", 1st Course: Current Topics in Astrofundamental Physics, edited by N. Svnchez and A. Zichichi, World Scientific (1992), pp. 224-233.

P.L. Richards, Bolometric Detectors for Infrared and Millimeter Waves, in *Infrared Astronomy from Space*, P. Encrenaz, F. Melchiorri, Eds., Scuola Superiore Reiss Romoli, L'Aquila, Italy, 1993, pp. 173-224.

C. Hagmann, D.J. Benford, A.C. Clapp, P.L. Richards, and P. Timbie, A Broadband THz Receiver for Low Background Space Applications, Third Int. Symposium on Space Terahertz Technology Proceedings, p. 678 (1992).

M. Devlin, D. Alsop, A. Clapp, D. Cottingham, M. Fischer, J. Gundersen, W. Holmes, A. Lange, P. Lubin, P. Meinhold, P. Richards, G. Smoot, Preliminary Results from the Third Flight of the Millimeter Anisotropy Experiment (MAX), Proc. Natl. Acad. Sci. 90, 4774 (1993).

C. Hagmann and P.L. Richards, Submillimeter Space Astronomy Without Liquid Helium, Proc. 7th Int. Cryocooler Conf. Part 3, 595 (1993).

P. Meinhold, A. Clapp, D. Cottingham, M. Devlin, M. Fischer, J. Gundersen, W. Holmes, A. Lange, P. Lubin, P. Richards, and G. Smoot, Measurements of the Anisotropy of the Cosmic Background Radiation at 0.5° Scale Near the Star μ Pegasi Ap. J. Lett. 409, L1 (1993).

M.J. Devlin, A. Clapp, M.L. Fischer, J.O. Gundersen, W. Holmes, A.E. Lange, P.M. Lubin, P. R. Meinhold, P.L. Richards, and G.F. Smoot, Results from the Third Flight of the Millimeter-Wave Anisotropy Experiment, Texas/PASCOS 92: Relativistic Astrophysics and Particle Cosmology Conference Proceedings, Editors: Carl W. Akerlof and Mark A. Srednicki, Annals of the New York Academy of Sciences 688, 809 (1993).

P.L. Richards, Bolometers for Infrared and Millimeter Waves, J. Appl. Phys. 76, 1 (1994).

J.O. Gundersen, A.C. Clapp, M. Devlin, W. Holmes, M.L. Fischer, P.R. Meinhold, A.E. Lange, P.M. Lubin, P.L. Richards, and G.F. Smoot, A Degree Scale Anisotropy Measurement of the Cosmic Microwave Background Near the Star Gamma Ursa Minoris, Ap. J. Lett. 413, L1 (1993).

A. Clapp, C. Hagmann, D. Benford, W. Holmes, and P.L. Richards, 100 mK Magnetic Refrigerators for Low Background Bolometric Receivers, SPIE Proc. Infrared Detectors and Instrumentation 1946, 126 (1993).

S.T. Tanaka, A. Clapp, M. Devlin, M. Fischer, C. Hagmann, A.E. Lange, and P.L. Richards, A 100 mK Bolometric Receiver for Low Background Astronomy, SPIE Proc. Infrared Detectors and Instrumentation 1946, 110 (1993).

P.L. Richards, A. Clapp, M. Devlin, M. Fischer, C. Hagmann, W. Holmes, A. Lange, S. Tanaka, P. Timbie, J. Gundersen, P. Meinhold, M. Lim, P. Lubin, G. Smoot, MAX Searches for Intermediate-Scale Anisotropy of the Cosmic Microwave Background, Infrared Phys. Technol. 35, 431 (1994).

C. Hagmann, D.J. Benford, and P.L. Richards, Paramagnetic Salt Pill Design for Magnetic Refrigerators Used in Space Applications, Cryogenics 34, 213 (1994).

M.L. Fischer, M. Devlin, A. Clapp, J.O. Gundersen, A.E. Lange, P.M. Lubin, P.R. Meinhold, and P.L. Richards, A Measurement of the Millimeter-Wave Spectrum of Interstellar Dust Emission, Ap. J. 444, 226 (1995).

P.L. Richards, Cosmic Microwave Background, in Galaxy Formation, Proc. Course CXXII Int. School of Physics Enrico Fermi, edited by J. Silk and N. Vittorio (North Holland, 1994) pp. 69-93.

M.J. Devlin, A.C. Clapp, J.O. Gundersen, C.A. Hagmann, V.V. Hristov, A.E. Lange, M. Lim, P.M. Lubin, P.D. Mauskopf, P.R. Meinhold, P.L. Richards, G.F. Smoot, S.T. Tanaka, P.T. Timbie, and A. Wuenche, Measurements of Anisotropy in the Cosmic Microwave Background Radiation at 0.5 Degree Angular Scales Near the Star Gamma Ursae Minoris, Ap.J. Lett. 430, L1 (1994).

A.C. Clapp, M.J. Devlin, J.O. Gundersen, C.A. Hagmann, V.V. Hristov, A.E. Lange, M. Lim, P.M. Lubin, P.D. Mauskopf, P.R. Meinhold, P.L. Richards, G.F. Smoot, S.T. Tanaka, P.T. Timbie and C A. Wuenche, Measurements of Anisotropy in the Cosmic Microwave Background Radiation at Degree Angular Scales Near the Stars Sigma Hercules and Iota Draconis, Ap.J. Lett. 433, L57 (1994).

M. Lim, J. Gundersen, P. Lubin, P. Meinhold, A. Wuenche, A. Clapp, M. Devlin, C. Hagmann, V. Hristov, A. Lange, P. Mauskopf, P. Richards, G. Smoot, and S. Tanaka, CMB Anisotropy Measurements During the Fourth Flight of MAX in CMB Anisotropies Two Years After COBE: Observations, Theory and the Future, Proc. 1994 CWRU Workshop, Editor: Lawrence M. Krauss, World Scientific Publishers, Singapore, 1994, pp. 51-56.

S. Tanaka, D. Alsop, E. Cheng, A. Clapp, D. Cottingham, M. Devlin, M. Fischer, J. Gundersen, C. Hagmann, W. Holmes, V. Hristov, T. Koch, E. Kreysa, A. Lange, M. Lim, P. Lubin, P. Mauskopf, P. Meinhold, P. Richards, G. Smoot, and P. Timbie, The Millimeter Wave Anisotropy Experiment (MAX), *Astro. Lett. and Commun.* 32, 223 (1995).

S.T. Tanaka, A.C. Clapp, M.J. Devlin, N. Figueiredo, J.O. Gundersen, S. Hanany, V.V. Hristov, A.E. Lange, M.A. Lim, P.M. Lubin, P.R. Meinhold, P.L. Richards, G.F. Smoot, and J. Staren, Measurements of Anisotropy in the Cosmic Microwave Background Radiation at 0.5° Scales near the Stars HR5127 and ϕ Herculis, *Ap.J.* 468, L81 (1996).

P. de Bernardis, P. Ade, E. Aquilini, J. Bock, A. Boscaleri, P. Cardoni, K. Ganga, M. Giacometti, M. Griffin, S. Hanany, V. Hristov, A. Lange, A. Lee, L. Martinis, S. Masi, P. Mauskopf, F. Melchiorri, P. Palangio, E. Pascale, A. Raccanelli, P. Richards, G. Romeo, F. Scaramuzzi, and D. Sforza, BOOMERanG: Balloon Observations of Millimetric Extragalactic Radiation and Geophysics, in Microwave Background Anisotropies, Edited by F.R. Bouchet, R. Gispert, B. Guiderdoni, and J. Tran Thanh Van (Editions Frontieres, 1997) pp 155-160.

A. Lee, P. Ade, J. Bock, A. Boscaleri, S. Church, P. de Bernardis, J. Feldman, K. Ganga, S. Hanany, V. Hristov, A. Lange, E. Pascale, P. Mauskopf, P. Richards, G. Smoot, S. Tanaka, C. Winant, and J. Wu, Future Plans for CMB Anisotropy Measurements with the MAXIMA Array, in Microwave Background Anisotropies, Edited by F.R. Bouchet, R. Gispert, B. Guiderdoni, and J. Tran Thanh Van (Editions Frontieres, 1997) pp 149-153.

S. Hanany and the MAX & MAXIMA Collaborations, The MAX and MAXIMA Experiments, in Microwave Background Anisotropies, Edited by F.R. Bouchet, R. Gispert, B. Guiderdoni, and J. Tran Thanh Van (Editions Frontieres, 1997) pp 143-148.